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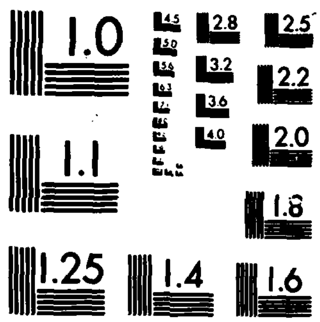

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Monterey, California

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SIMULATION AND PERFORMANCE OF BRUSHLESS
DC MOTOR ACTUATORS

Alex Gerba Jr.

December 1985

Progress Report for Period

October 1984 - September 1985

Approved for Public Release; Distribution Unlimited
Prepared for: Naval Weapons Center, Code 3275
China Lake, California 93555

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Alex Gerba Jr.
Associate Professor of Electrical and Computer Engineering

Reviewed by:

Harriett B. Rigas
Chairman, Department of Electrical and Computer Engineering

Released by:

John N. Dyer
Dean of Science and Engineering

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Comparison of simulated model with the measured performance of a typical motor are done both on time response waveforms and on average performance characteristics. These preliminary results indicate good agreement. Plans for

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NAVAL POSTGRADUATE SCHOOL
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Progress Report

SIMULATION AND PERFORMANCE OF BRUSHLESS DC MOTOR ACTUATORS

IN SUPPORT OF THE PROGRAM
"ADVANCED MISSILE CONTROL DEVICES"

of the

Naval Weapons Center
China Lake, California

December 1985

For the period October 1984 - September 1985

SIMULATION AND PERFORMANCE OF BRUSHLESS DC MOTOR ACTUATORS

SUMMARY

The simulation model for a Brushless D.C. Motor and the associated commutation power conditioner transistor model are presented. The necessary conditions for maximum power output while operating at steady-state speed and sinusoidally distributed air-gap flux are developed.

Comparisons of simulated model with the measured performance of a typical motor are done both on time response waveforms and on average performance characteristics. These preliminary results indicate good agreement. Plans for model improvement and testing of a motor-driven positioning device for model evaluation are outlined.

TABLE OF CONTENTS

LIST OF SYMBOLS

B_m Viscous friction coefficient of the motor (oz-in/rad per sec)

B_l Viscous friction coefficient of the load (oz-in/rad per sec)

E_{BA} Back EMF of phase A (volts)

E_{BB} Back EMF of phase B (volts)

E_{BC} Back EMF of phase C (volts)

I_A Phase A current (amperes)

I_B Phase B current (amperes)

I_C Phase C current (amperes)

I_M Power supply current (amperes)

J_M Moment of inertia of motor shaft (oz-in-sec^2)

J_l Moment of inertia of load shaft (oz-in-sec^2)

k_b Back EMF constant (volts/rad per sec)

k_t Torque constant (oz-in/ampere)

L Inductance of the stator winding (Henrys)

I_{AB}, I_{CA}, I_{BC} Loop currents (amperes)

k_{adj} Air-gap flux adjustment factor

k_{wl} Magnitude of speed versus torque curve slope (rad per sec/oz-in)

R_a Resistance of the stator windings (ohms)

R_s Power supply interval resistance (ohms)

ϕ_A, ϕ_B, ϕ_C Per phase air-gap flux (webers)

R_q 'On' resistance of the power transistor (Ohms)

T_m Motor restraining torque (oz-in)

T_l Load restraining torque (oz-in)

T_A, T_B, T_C Per phase developed torque (oz-in)

w_m Speed of the motor shaft (rad/sec)

GR Gear ratio

θ Angular displacement (radians)

V_A, V_B, V_C Phase terminal voltage (volts)

V_S Power supply terminal voltage (volts)

RPSA, RPSB, RPSC Position sensors logic signals

PWM Pulse width modulation

INTRODUCTION

Recent improvements in rare-earth magnetic materials for use in brushless dc motors have allowed reconsideration of electro-mechanical actuator systems for applications requiring very high ratios of torque-to-inertia. The investigation discussed herein has been concerned with characterizing mathematically the dynamical features of a missile fin actuation system, from the input to the brushless dc motor to the output shaft of the mechanical actuator. The physical model is based upon an existing prototype actuator currently under evaluation at the Naval Weapons Center, China Lake, California.

In general, brushless dc motors produce torque through the interaction of a magnetic field generated by a permanent magnet rotor and a dc generated magnetic field in the stator. The rotating permanent magnet eliminates the rotating armature and the mechanical wear normally associated with brushes. These motors fall in the class of Permanent Magnet Motors and enjoy certain advantages over wound-field types such as:

> "...Linear torque-speed characteristics, high stall (accelerating) torque, no need for electric power to generate the magnetic flux and a smaller frame and lighter motor for a given output power" [1].

Additionally, the brushless dc motor is characterized by:

> "...controllability over a wide range of speeds, capable of rapid acceleration and deceleration, convenient control of shaft speed and position, no mechanical wear problem due to commutation and better heat dissipation arrangement" [1].

The fundamental requirement of an electro-mechanical actuator control system is to provide torque to an output shaft, sense the position of the shaft and adjust the torque to balance the load when the desired position is reached. This must be accomplished with a minimum of frictional resistance and delays associated with the inertia of the mechanical components. Effects of viscous, static and coulomb friction, together with the torque required to accelerate the mechanical components of the system, lead to a reduction in

torque available at the output shaft and an associated reduction in system performance.

One approach to the analysis of the electro-mechanical actuator system has been to divide the system into two sequential problem areas. The first deals with the dynamic analysis of the brushless dc motor and development of the transfer function necessary to duplicate actual steady-state and transient performance. The second area deals with modeling the mechanical system elements, taking as input the dc motor shaft angular acceleration predicted by the motor analysis. The mechanical system must be modeled considering the effects of friction and inertia and translating the rotational motion of the brushless dc motor shaft to the output shaft of the actuator for application to missile maneuvering control. The results obtained from a study that has placed primary emphasis upon the latter problem area - the modeling of the mechanical drive-train leading to the fin shaft was presented in Ref. 3 and 4.

This report deals with the first problem area and presents an overview of the work done by MacMillan [4]. In Ref. 4, MacMillan developed a model for the output circuitry of a transistorized power conditioner that provided the required motor commutation. The model developed in Ref. 4 used an ideal (zero impedance) power supply. This report extends the model to include internal power supply resistance and also identifies areas for further improvement in the system modeling.

The next section of this report presents a brief description of the system followed by a development of the model and an analysis of the simulated motor performance. Results of the simulated system are then compared to the measured response from a typical commercially available motor and recommendations for further improvements in the model are outlined.

SYSTEM DESCRIPTION

GENERAL

The system is viewed as a position control device to maintain an output angle under an applied hinge moment due to aerodynamic forces on a fin or aileron. The motor is a permanent magnet dc motor with feedback in the form of back emf proportional to the angular velocity of the motor. The block diagram of the dc motor and power conditioner is shown in Fig. 1 [4]. The mechanical actuator and drive train, as currently envisioned, introduce various inertial and damping loads together with an aerodynamic force and its associated fin hinge moment that must be overcome to produce output motion. An operational block diagram of the load torque is shown in Fig. 2 where the hinge moment and motor shaft angular acceleration are viewed as inputs to the drive train [2]. Figure 3 is a schematic of the drive train which, as presently constituted, includes the motor shaft (leadscrew), ball screw assembly, and the crank which is keyed to the output (fin) shaft. Inertial loads are considered individually within three major subdivisions of the actuator; the output shaft to crank, crank to ball screw, and ball screw to leadscrew.

A detailed analysis and development of the mechanical model with the associated assumptions are contained in Reference 2. As stated in the introduction, this report reviews the development of the motor model reported in Reference 4. For convenience in the development of the model, MacMillan considered the load seen by the motor to be caused by the inertia and kinetic (viscous) friction of the motor shaft as described by Thomas in Reference 5.

The schematic diagram of the power supply, power conditioner and motor-load is shown in Figure 4 where it is noted that the power conditioner logic and driver circuits are modeled as ideal on-off devices with zero time delay.

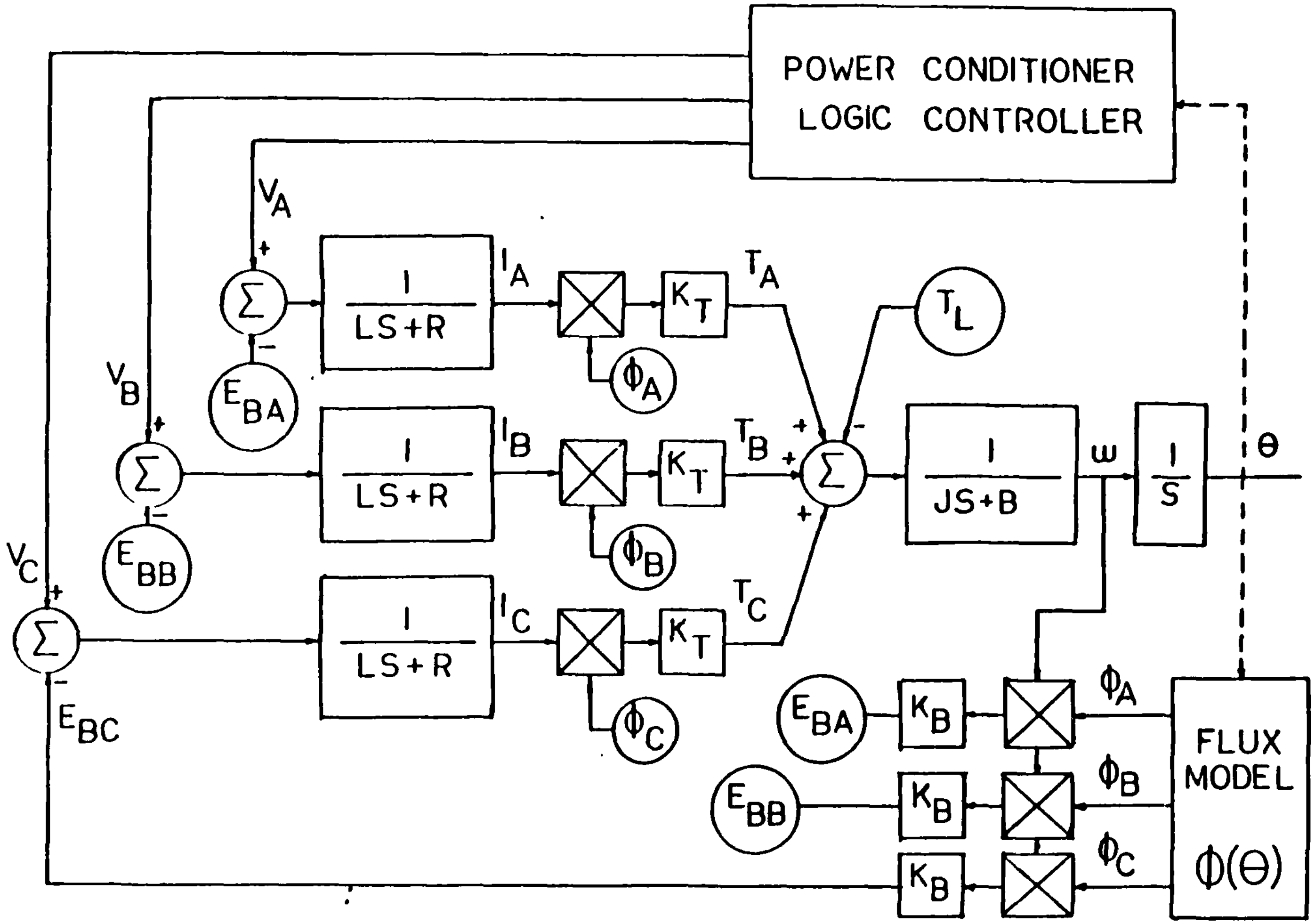


Figure 1 Motor and Power Conditioner Simulation Diagram

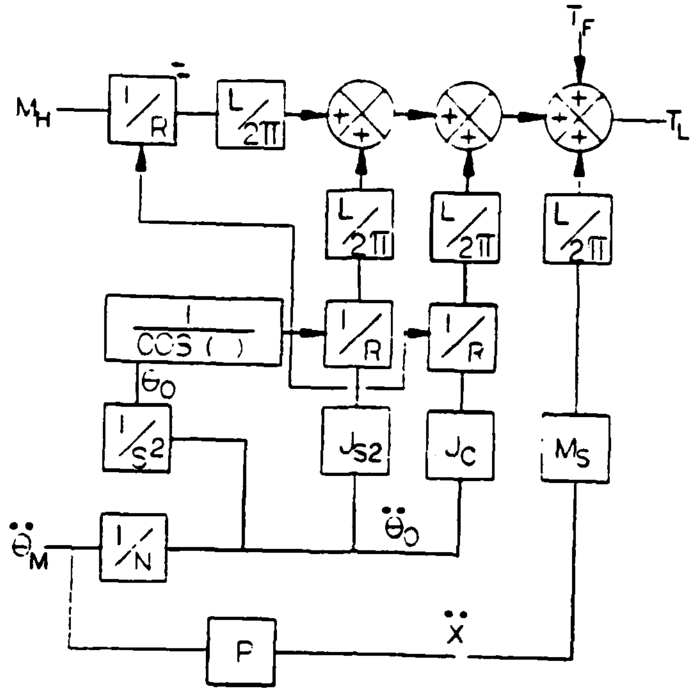


Figure 2 Load Torque Block Diagram

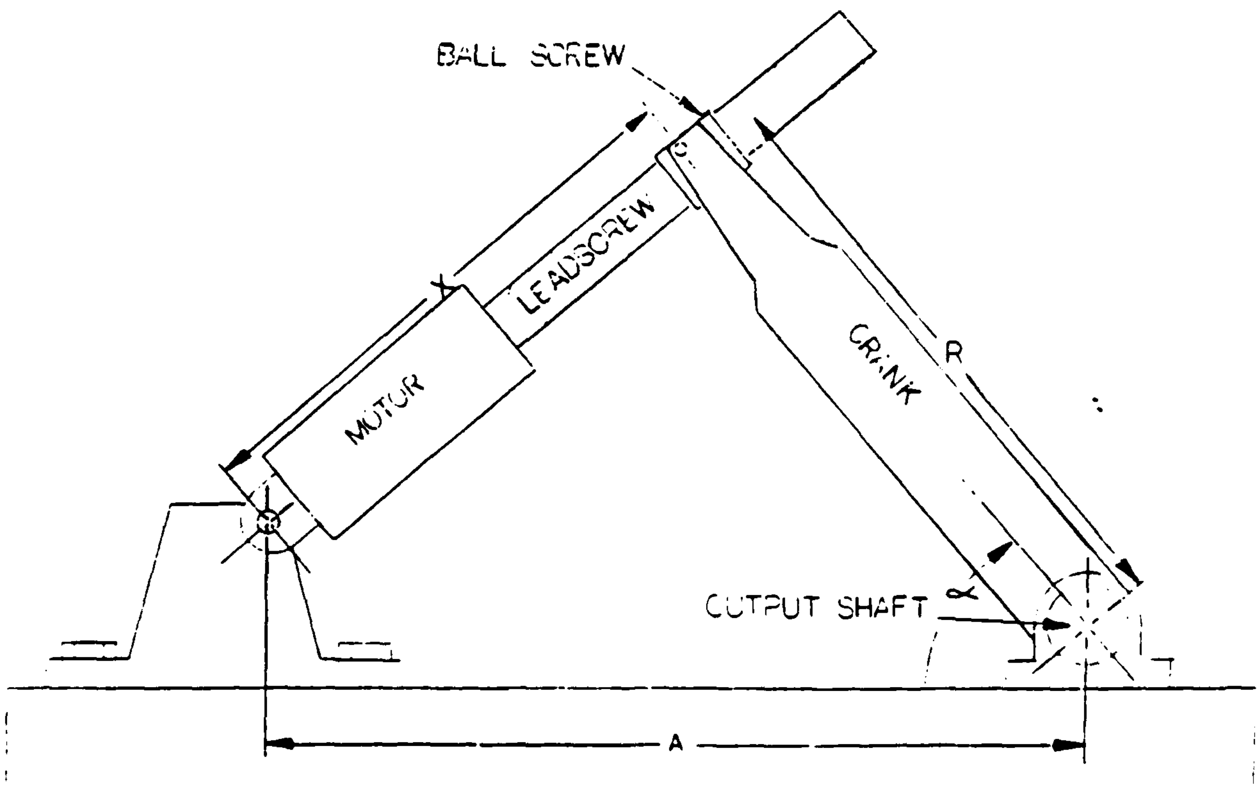


Figure 3 Sketch of Actuator Arrangement

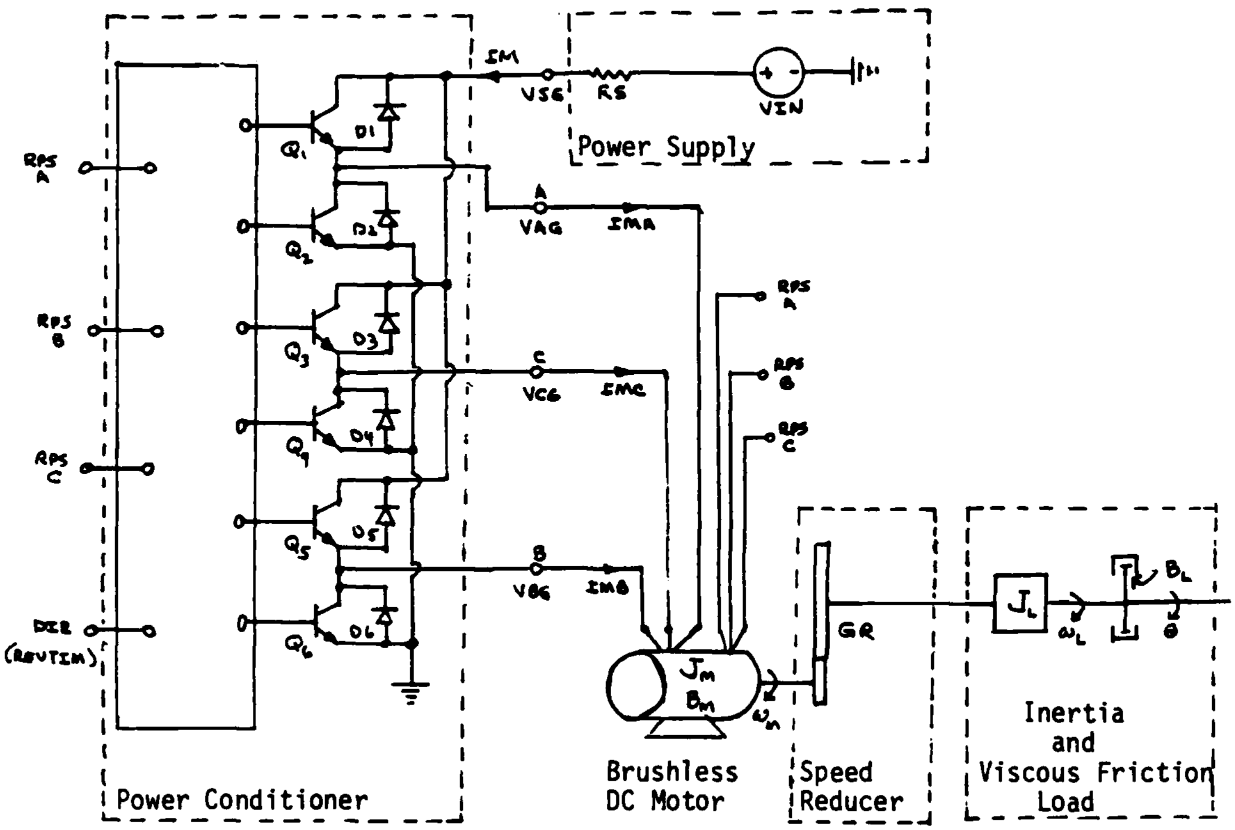


Figure 4 Schematic Diagram of Power Supply, Power Conditioner and Motor with Inertia and Viscous Friction Load.

Additionally, MacMillan considered the power supply to be ideal (zero interval resistance) to further reduce the complexity and simplify the development of the power conditioner model. However, in this report, the model used for the power supply includes the internal resistance, R_s. The effect of including R_s in the requirements and performance of the system model is presented in the section on Analysis of Simulated Motor Performance. For additional information on the development of the D.C. motor model refer to Reference 4.

DEVELOPMENT OF SYSTEM MODEL

The basic simulation by Thomas used a single power supply and superimposed the phase currents to produce the motor torque. Motor drive was then realized by multiplying averaged armature current by a torque factor.

In the model developed by MacMillan, the supply is considered to be a split supply of equal voltages. Armature current is assigned a positive sign if it flows in the positive direction (i.e. into the motor). The use of a split power supply allowed MacMillan to apply circuit reduction techniques. Because of the symmetry that resulted from the split power supply approach, the complex 3-phase bridge-type circuit simplified into a two-window network. The development of the reduced circuit begins with the definitions of loop currents as shown in Figure 5 where the power supply voltage of 2V is represented as V+ and V-. The simulated model equivalent circuit is shown in Fig. 6 with node N defined as the mid-point of the power supply and node 0 to be the mid-point of the motor windings and neither of these nodes are considered to be at ground potential (the ground is identified as the Reference node). Note that the power supply, VIN = VIF - VIB = 2V and that all the network variables are defined using the CSMP model variable definitions [6]. Given the assumption that the network is balanced, that is,

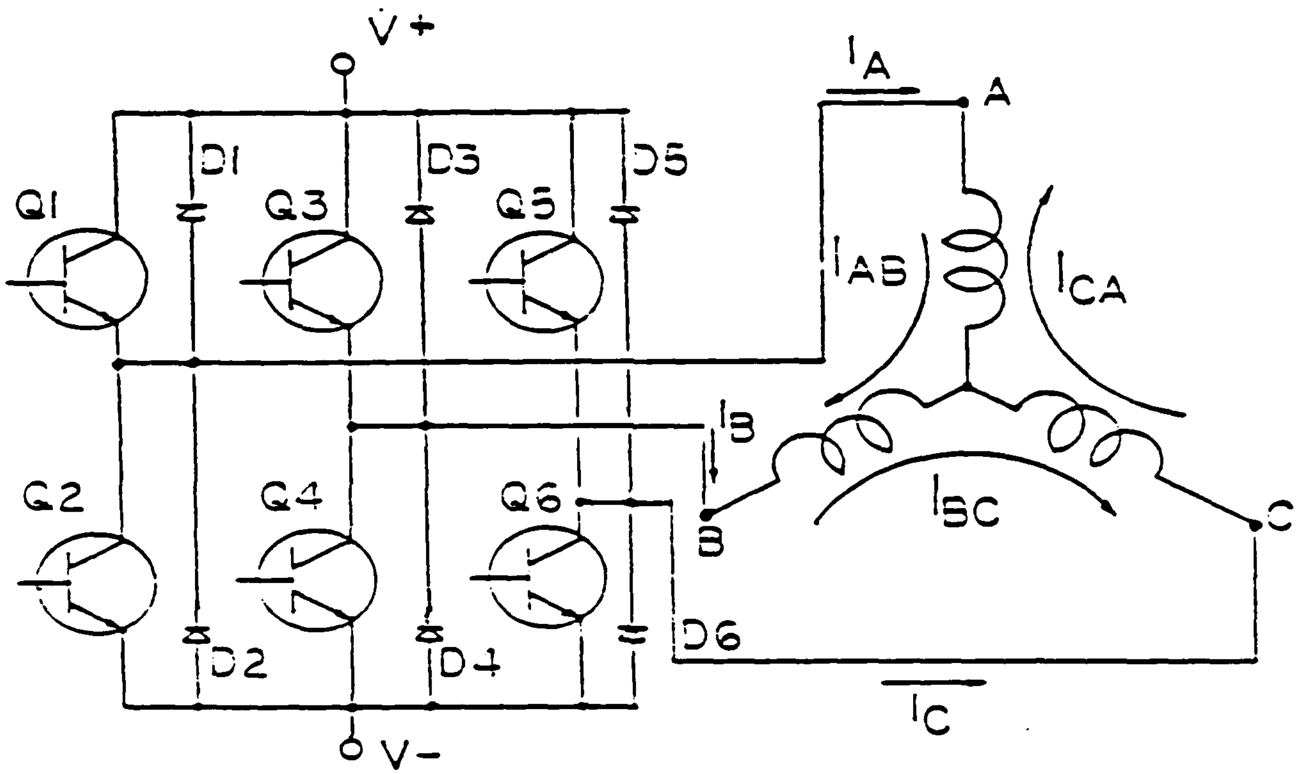


Figure 5 Motor and Commutating Transistors

all transistors, diodes and field windings are approximated as being alike in characteristics, it is possible to apply the circuit reduction technique of Thevenin and obtain the simple 2-window network shown in Figure 7 [4]. In Figure 7, the Thevenin equivalent voltages and currents are defined in terms of the CSMP model variables.

The back emf voltages of each phase (VEMFA, VEMFB and VEMFC) are developed and presented in Reference 4 in which it is shown that these voltages are summed 2 at a time in proper sequence to compute the loop currents and resulting phase torque. The total developed torque is then the sum of the 2-active winding phase torques over the proper 60 degree of mechanical angle. Figure 8 shows the back emf voltages generated across 2 windings taken 2 at a time. The 60 degree of mechanical angle that produces torque is shown by the logic unit output levels of the position transducer RPSA, RPSB and RPSC in Figure 8.

Reference 4 presents a detailed development of the power conditioner model that includes the assumptions for the switching transistor dynamics used in the power conditioner model as well as the development of the harmonic air-gap flux used in the motor model.

ANALYSIS OF SIMULATED MOTOR PERFORMANCE

The proper evaluation of a system model requires, quite naturally, a comparison of the actual system response for the same type of input function used for the model. For the brushless D.C. motor, it is assumed that measurements can be obtained for the following voltages and currents:

- Power supply terminal voltage; V_{sg}
- Voltage across two of the three windings; V_{ab}, V_{bc}, and V_{ca}

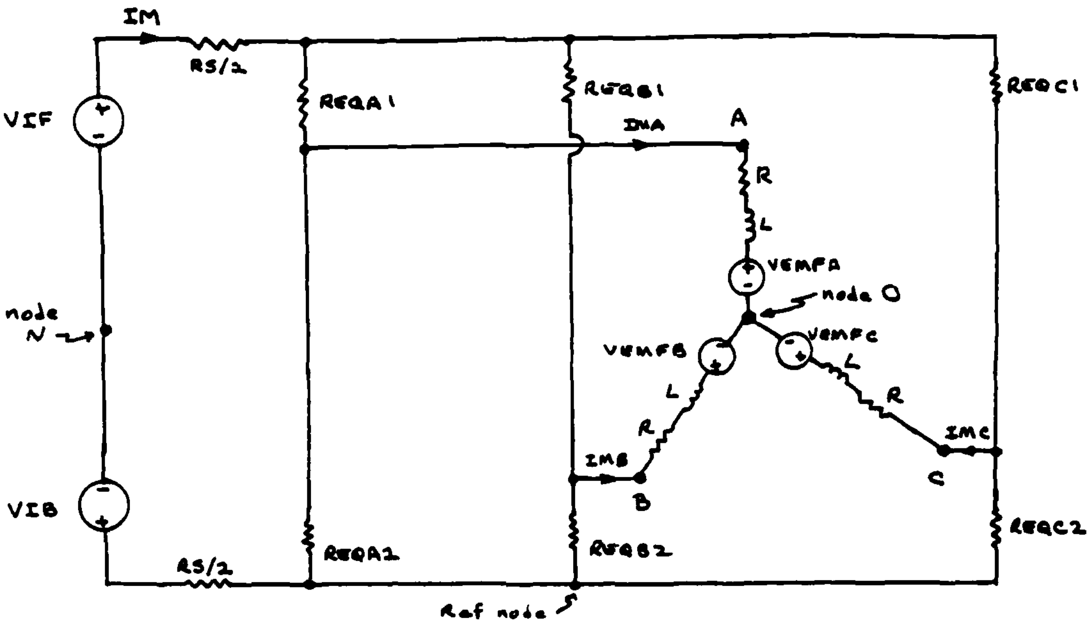


Figure 5 Split Power Supply Bridge-Type Circuit Model

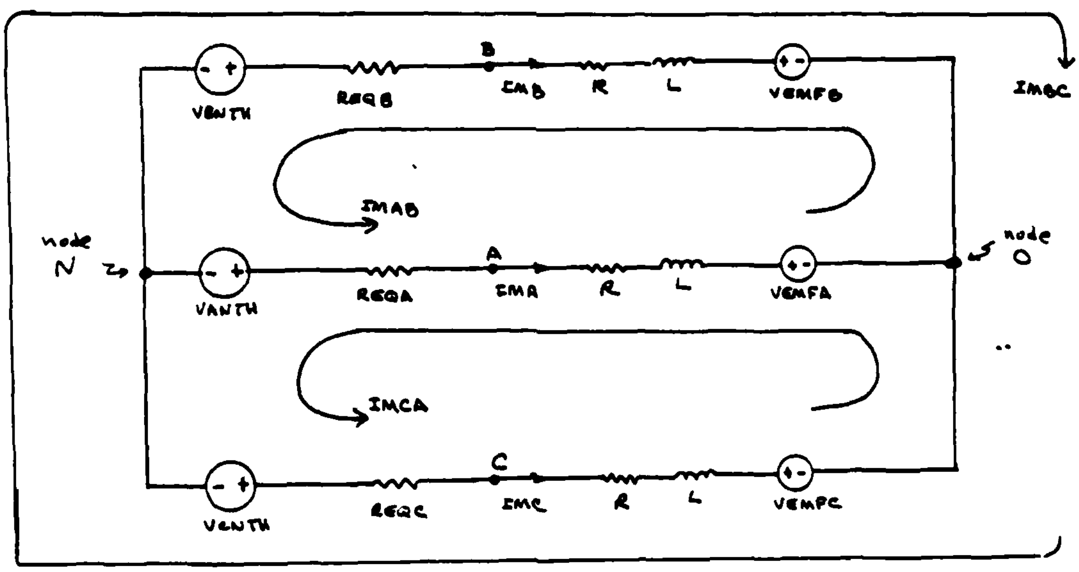
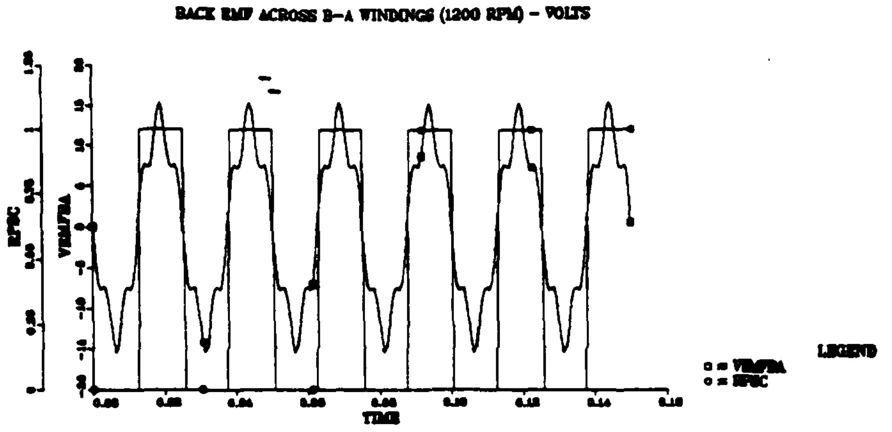
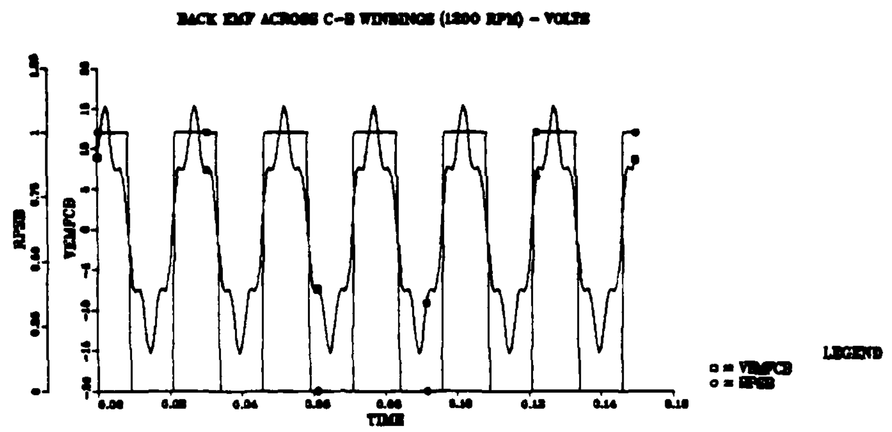


Figure 6 Two-Window Equivalent Circuit of the Balanced Bridge Network





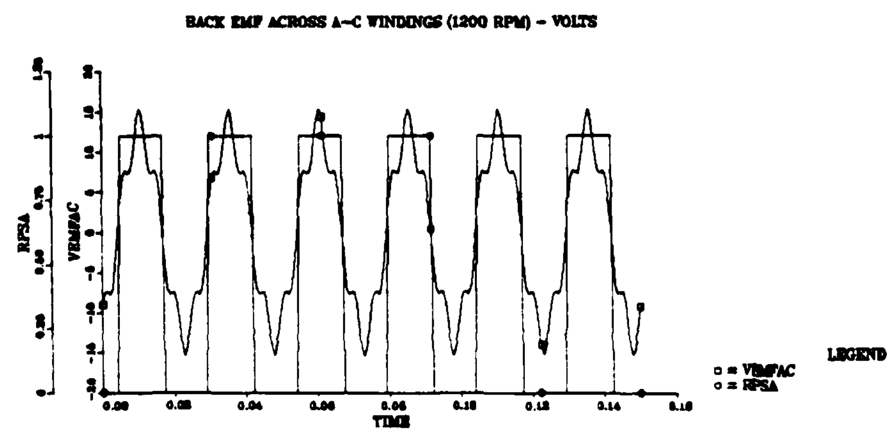


Figure 8 Back EMF and Position Sensor Output with Motor Driven at 1200 RPM (CCW)

- Voltage from one winding terminal to ground; V_a, V_b and V_c
- Power supply current; I_m
- Phase current; I_{ma}, I_{mb}, I_{mc}

Before taking data from the simulated model, it is necessary to set all constants and parameters to the nominal values given by the supplier of the motor. Care must be taken to properly interpret the values given by the manufacturer.

In particular, the value of the Back EMF coefficient, k_b, needs special attention. If the motor data sheet indicates that this coefficient is obtained by measurement of peak to peak voltage across two windings, then in the model that uses distributed sinusoidal air-gap flux, an adjustment factor, k_{adj} is required to insure that the Back EMF values are in agreement. It follows that the torque coefficient, k_t, must also be adjusted by this same scale factor [7]. The value of k_{adj} can be computed from the measured no-load data for the motor current, speed and applied voltage by using the average characteristics balance equation,

$$i_m = (v_{sg} - k_b w_{nl})/(R_a + R_q)$$

where $k_b = k_{bm} k_{adj}$

k_{bm} = manufacturer supplied Back EMF constant.

Thus the adjustment factor becomes

$$k_{adj} = [v_{sg} - i_m(R_a + R_q)]/(k_{bm} w_{nl})$$

For example, given a no-load speed of 3060 RPM with a terminal voltage of 30 volts and a no-load current of 0.30 amperes, $k_{adj} = 0.825$ (given a total series resistance of 1.47 ohms). The value of k_{adj} must of course be less than unity, otherwise the motor current would be negative in value which implies that generator rather than motor action is taking place.

Before an attempt is made to close the loop on the motor-load to form a positioning device, it is important to operate the system as a velocity device and obtain measurement of the motor average performance characteristics. Typical motor average performance curves are speed versus torque, motor current versus torque and output power versus torque from no-load torque to near stall torque conditions. Figure 9 shows these three curves for the model with torque given in oz-in units. Note in particular the straight line characteristics for motor speed and current and that the power output is of quadratic form. The condition of constant input voltage is used when gathering data for these curves, and it follows that if speed is a straight-line versus torque, then current also has a straight-line when plotted against torque. This can be shown as follows:

$$w_m = w_{nl} - k_{wl}T$$

where w_m = motor speed

w_{nl} = no-load speed

k_{wl} = magnitude of slope of the speed vs torque curve

T = load torque

The current, using average values, can be written as

$$i_m = (v_{sg} - k_b w_m)/(R_a + R_q)$$

where v_{sg} = power supply terminal voltage

k_b = Back EMF coefficient

R_a = winding resistance

R_q = transistor "ON" resistance

then by substitution,

$$i_m = [(v_{sg} - k_b\, w_{nl})/(R_a + R_q)] + [(k_b k_{wl})/(R_a + R_q)]T$$

where the first term on the right hand side of the equation represents the no-load current.

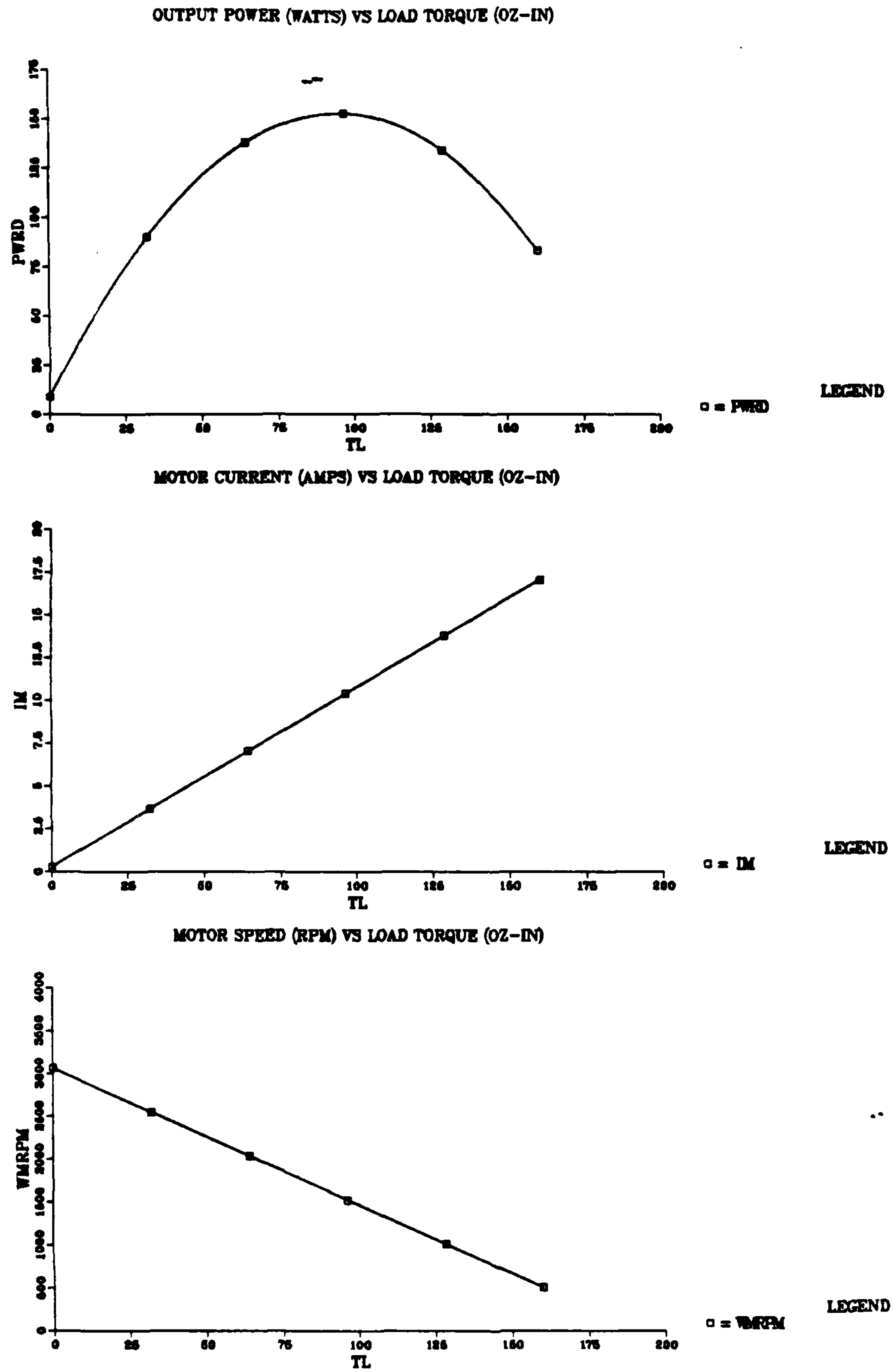


Figure 9 Average Performance Characteristics of the Simulated Model

The power output versus torque curve in Figure 9 reaches a peak value between no-load torque and stall torque. The analytical development for this quadratic curve is presented in Appendix A where it is shown that the condition for peak power output, P_o, is that the torque must be of value

$$T = (2k_b w_{nl} - v_{sg})/(2k_b k_{wl})$$

to produce maximum power output

$$P_o = k_t v_{sg}^2/(4R_s k_b)$$

Since the ratio k_t/k_b is a constant, increasing peak power output depends upon decreasing the power supply interval resistance, R_s, or increasing the power supply voltage, v_{sg} as one would logically expect. It must be understood that the assumption used in the above analysis was that the air-gap flux was a constant average value. For the actual motor the air-gap flux is distributed sinusoidally and current in the windings produces a field that may cause distortion in the air-gap flux. At large current values that occur at and above peak power output, the field distortion may result in an increase or a reduction of output power for a given load torque.

Another motor coefficient to consider carefully is the no-load viscous friction constant, B_m. The value of B_m is often not included in the motor data sheet and the probable reason is that its value will depend somewhat on the manner in which the motor is attached to the system load. B_m can be calculated from given no-load data as follows:

$$B_m = (k_t \; k_{adj} \; i_m)/w_{nl}$$

where i_m is the no-load current.

RESULTS AND CONCLUSIONS

The preliminary results indicate that the balanced bridge circuit approach used in the development of the Brushless DC motor model produces good

agreement with measured motor characteristics as indicated below. Further evaluations of the model as well as improvements and additions to the model will be conducted in the near future using data currently being gathered from a prototype of a fin positioning actuator.

A comparison of model and motor produced Back EMF voltage is shown in Figure 10. The upper curve is the simulated motor waveform and the lower curve is the measured Back EMF. The model adjustment factor, k_{adj} was set to 0.63 value by trial and error until peak to peak voltages were in agreement. Another verification of the model is obtained by comparison of Figure 11 and Figure 8. Both figures show waveforms of Back EMF across 2 windings taken 2 at a time and also show the timing waveforms for the Position Sensor Devices (RPSA, RPSB and RPSC) for counter clockwise rotation. The waveforms agree in both phasing and in form.

The steady-state performance curves of a typical motor are given in Figure 12 where the motor load torque is given in lb in units. These curves were produced with a constant terminal voltage of 30 volts and agree in form with the curves of the model as given in Figure 9. Peak power output occurs at load torque of approximately 95 oz-in for both motor and model.

Additional validation of the model is shown in Figure 13 where the current in Phase C for the model (upper curve) is in close agreement both in form and in phase with the same current for the motor (lower curve). Additional model results are shown in Appendix B where typical input voltage step response waveforms are presented.

FURTHER RESEARCH

Improvements in the model are required with regard to the triggering on of the diodes used to protect the transistors from excessive reverse currents

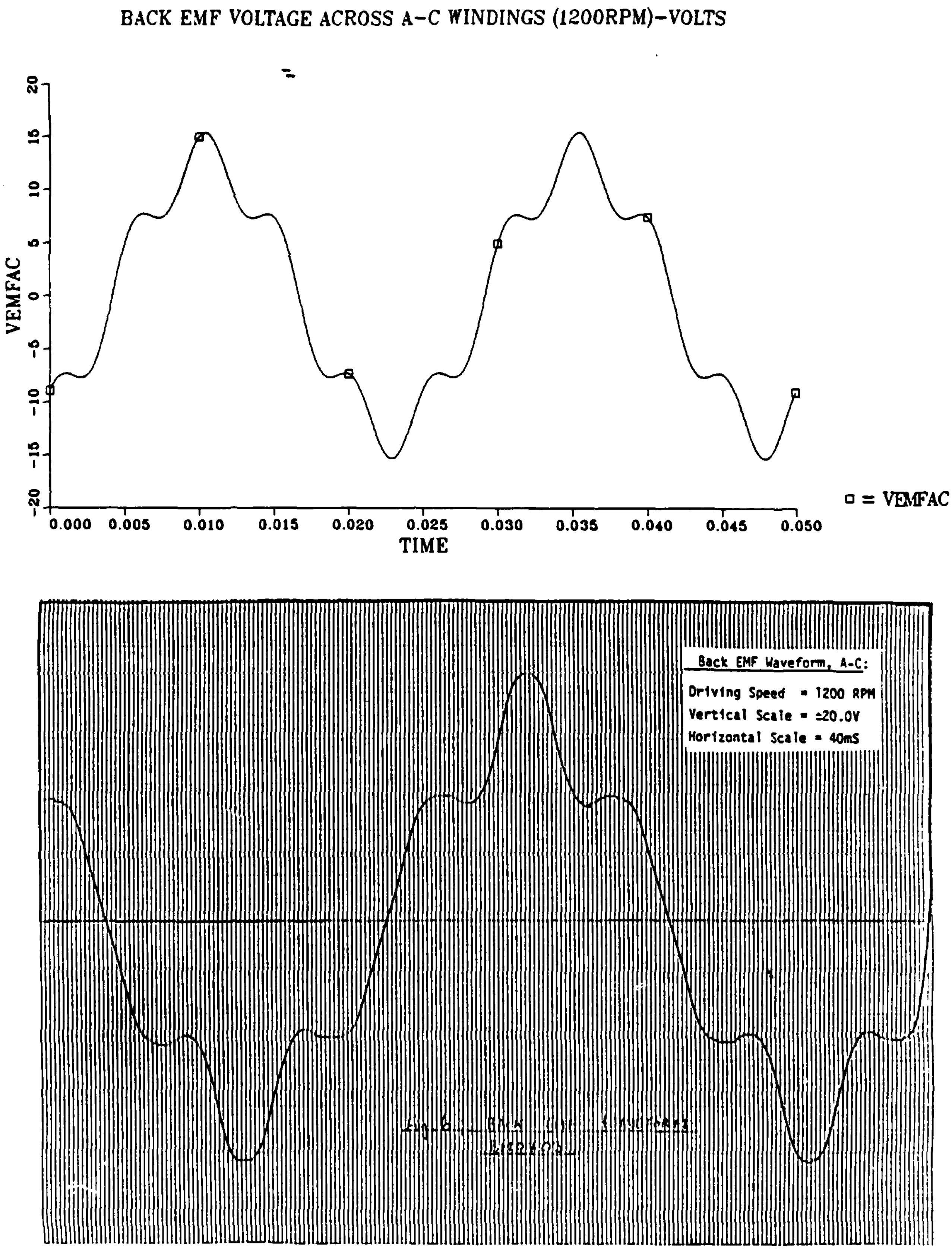


Figure 10 Back EMF Voltage: Top Curve-Model Output,
Bottom Curve-Typical Motor Output

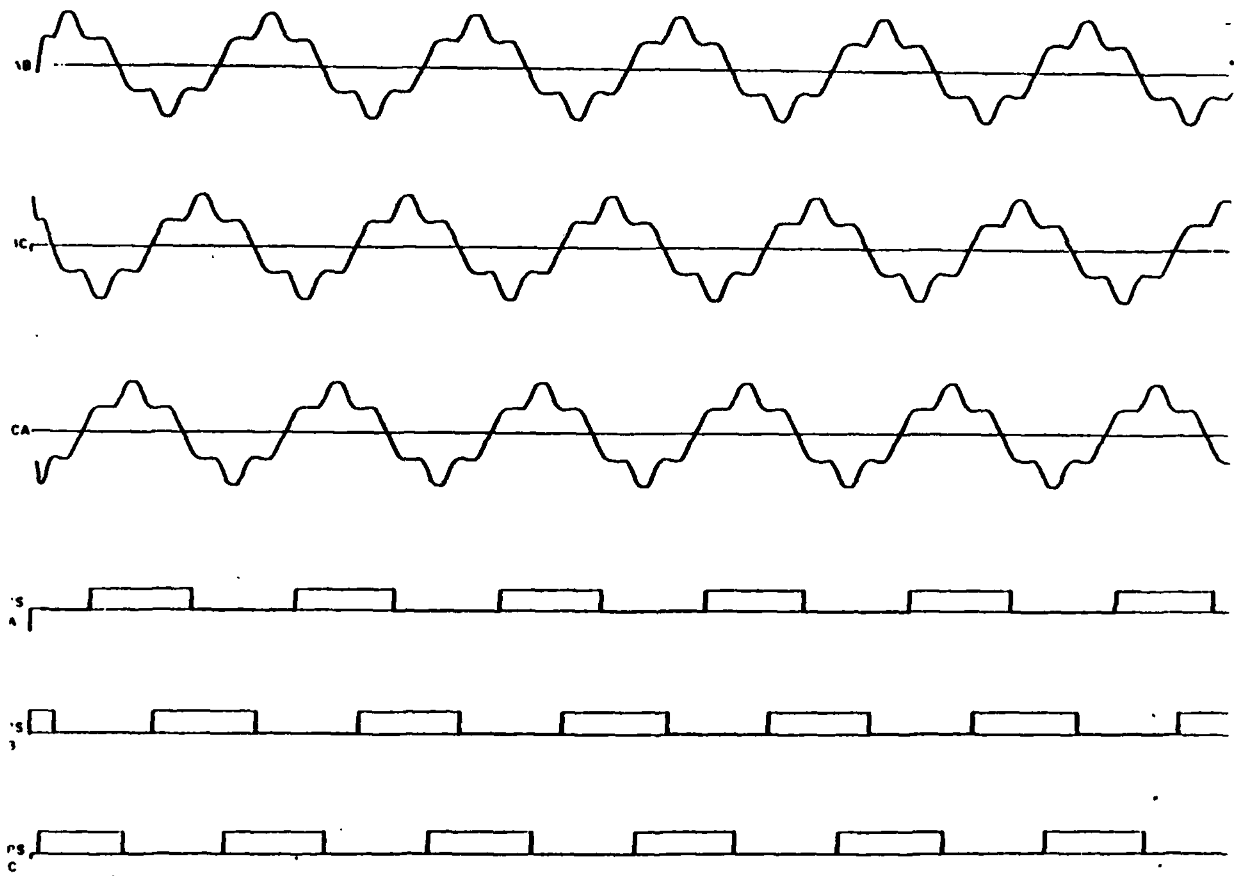


FIGURE 1.
BACK EMF & RPS WAVEFORMS
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Figure 11 Back EMF and Position Sensor Output Waveform for a Typical Motor

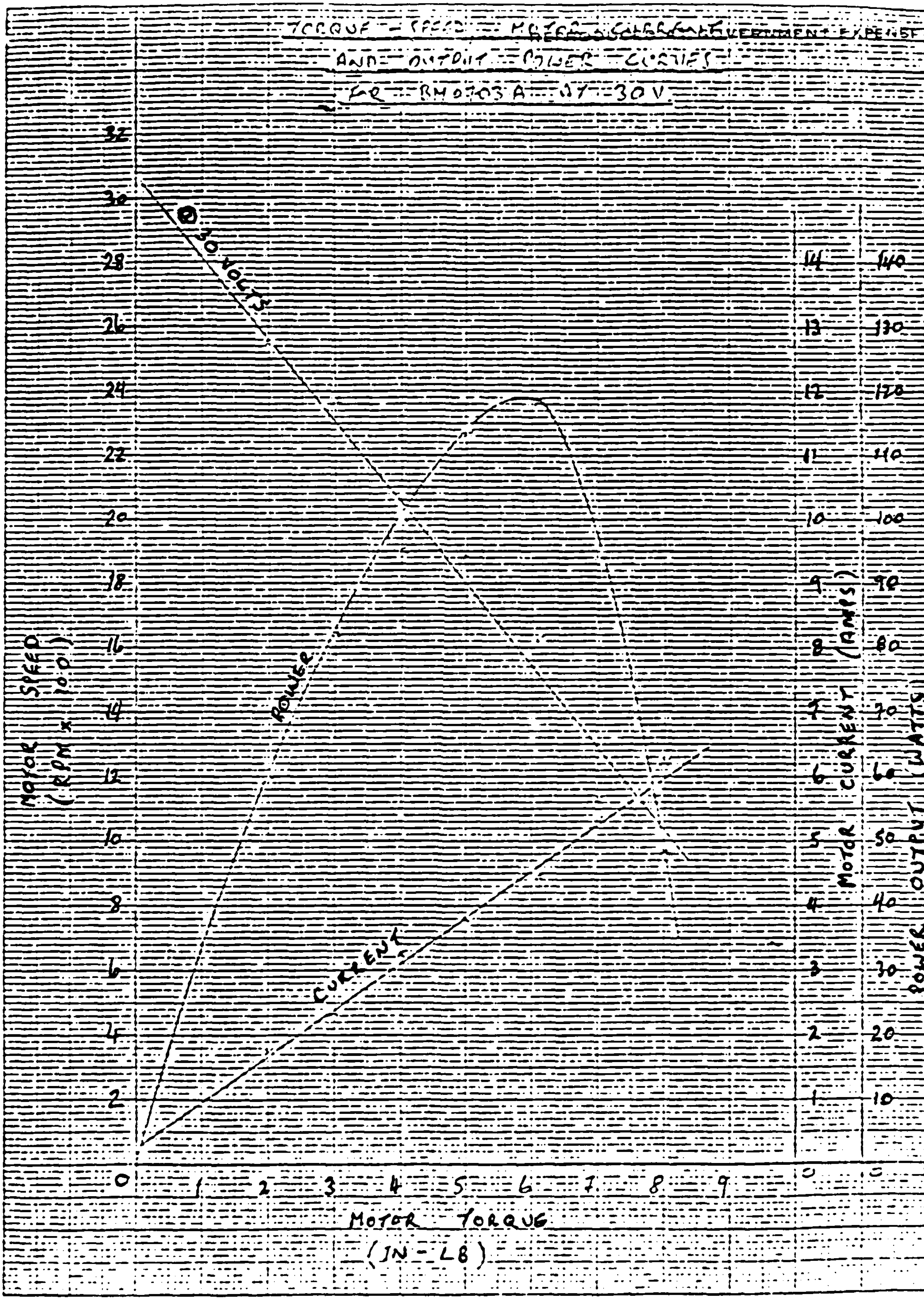

Figure 12 Typical Measured Motor Performance

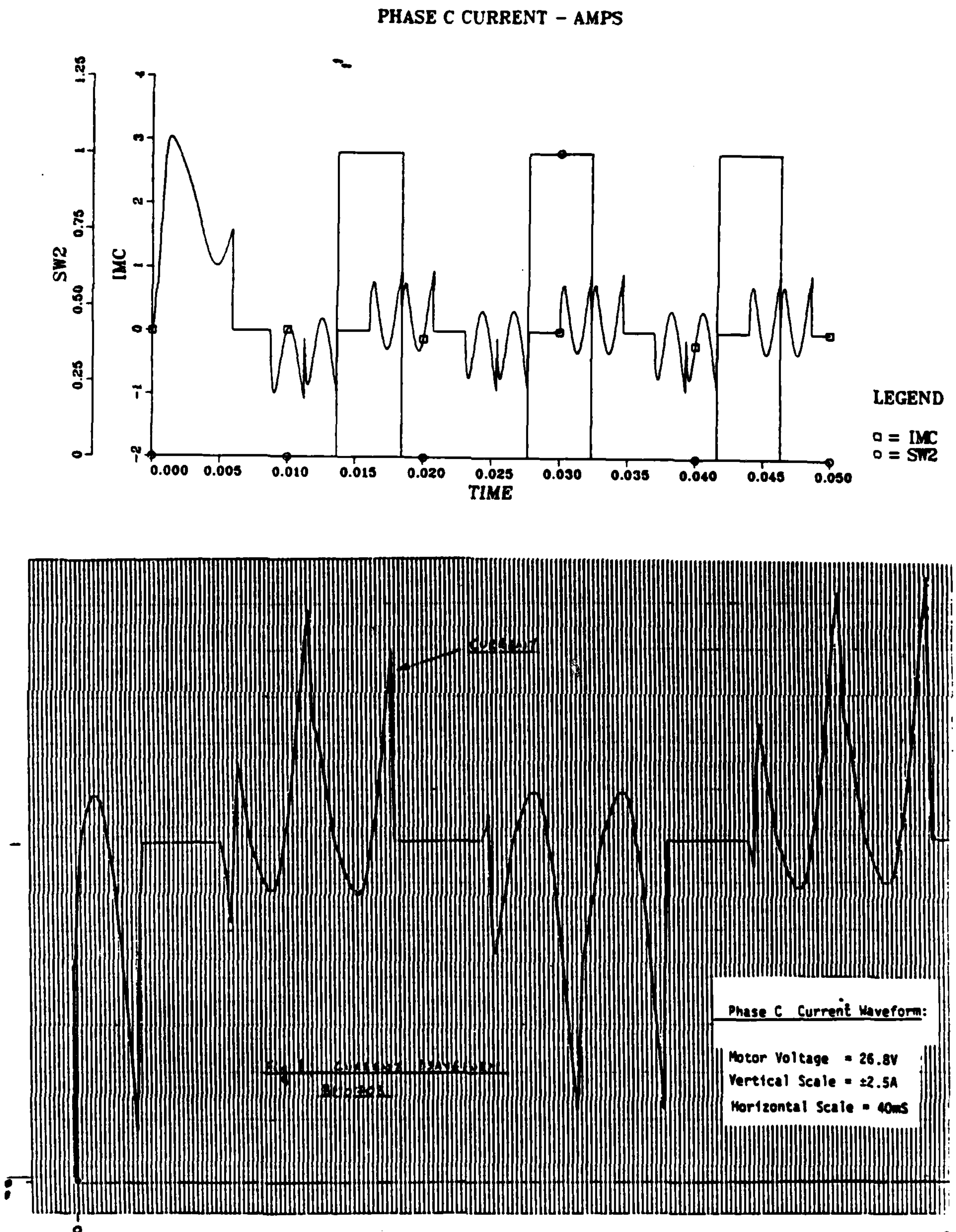

Figure 13 Phace C Current: Top Curve-Simulated Módel,
Lower Curve-Typical Motor

during the switch off time for the transistors. MacMillan in Ref. 4 was able to provide this action for the condition that the power supply interval resistance, R_s is zero value. When R_s is not zero, additional programming is required to perform the required trigger action.

The Pulse Width Modulation (PWM) used by Askinas in Ref. 8 must be added to the present model, however Askinas used a separate additional transistor to perform PWM. The Power Conditioner to be used in the Test Stand for measurement of actuator performance accomplishes PWM by using the lower set of the commutating power transistors. Therefore some modification of Askinas' CSMP coding may be required to accurately perform the PWM speed control.

Extensions of the model will include a position sensing device and a tachometer as well as the nonlinear loading as developed by Franklin in Ref 9. Test data results will be compared to model in both transient (step) response and in frequency (Bode) response and the results will be reported in a Summary Report for FY1986.

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the rate of change and set it equal to zero. Thus,

$$\frac{dP_o}{dT_L} = -\frac{k_t k_{wl} v_{sg}}{R_A + R_q} + \frac{2k_t k_b k_{wl} w_{nl}}{R_A + R_q} - \frac{2k_t k_b k_{wl}^2}{R_A + R_q} T_L = 0$$

Solving for load torque, TL yields

$$T_L = w_{nl}/k_{wl} - v_{sg}/(2k_g k_{wl})$$

$$T_L = (2k_b w_{nl} - v_{sg})/(2k_b k_{wl})$$

and substitution into the power output equation produces the conditions for peak power output as follows:

$$P_o = k_t v_{sg}/(R_a+R_q)[w_{nl}-k_{wl}(2k_b w_{nl}-v_{sg})/(2k_b k_{wl})]$$
$$- k_t k_b/(R_a+R_q)[w_{nl}-k_{wl}(2k_b w_{nl}-v_{sg})/2k_b k_{wl})]^2$$

After expansion and cancellation of like terms, the peak power output reduces to

$$P_o = k_t v_{sg}^2/[4k_b(R_a+R_q)]$$

As a numerical example consider the following values of a typical Brushless DC Motor operating at a steady-state speed of 3060 RPM (320.4 rad/sec) with a constant terminal voltage of 30 volts.

k_t = 15.9 oz-in/ampere

k_b = 0.112 volts/rad per sec

k_{adj} = 0.825

R_a = 1.37 ohms, R_q = 0.10 ohms

k_{wl} = 1.67 rad per sec/oz-in

Thus for this example motor,

$$P_o = (15.9)(0.825)(30)^2(7.062\times10^{-3})/[4(.112)(0.825)(1.47)$$

$$P_o = 153.5 \text{ watts}$$

and occurs at load torque

$$T_L = [(320.4)/(1.67) - (30.)/(2)(.112)(.825)(1.67)]$$

$$T_L = 94.65 \text{ oz-in} = 5.92 \text{ lb-in}$$

APPENDIX A

Power Output of a Brushless DC Motor

The mechanical power developed by a Brushless DC Motor is given by the equation,

$$P = (7.062 \times 10^{-3})\ T w_m \text{ watts}$$

where $T = T_L + T_M$, the sum of the load torque, T_L and the motor restraining torque, T_M in oz-in units and w_m is the motor speed in rad/sec. units. At no load $T_L = 0$ and at stall torque $w_m = 0$, thus power reaches a peak value in the region between no load and stall torque conditions.

The evaluation of steady-state peak power can be obtained analytically in terms of the load torque by substitution as shown below.

Given that $T = T_L$ that is $T_L \gg T_M$ and $T = k_t i_m$ with $w_M = w_{NL}$ where k_t is the motor torque coefficient and k_{wl} is the slope of the speed-torque curve. Then the power output is

$$P_o = k_t i_m (w - k_{wl} T_L)$$

and since steady-state speed conditions are assumed, the current is given by

$$i_m = \frac{v_{sg} - k_b w_m}{R_A + R_q}$$

where v_{sg} is the voltage at the terminals of the power supply, k_b is the Back EMF coefficient, R_a is the armature resistance of 2 phases in series and R_q is the sum of 2 power transistors forward conduction resistance. By substitution,

$$P_o = \frac{k_t v_{sg}}{R_a + R_q} (w_{nl} - k_{wl} T_L) - \frac{k_t k_b}{R_A + R_q} (w_{nl} - k_{wl} T_L)^2$$

and to find the conditions for peak power output, it is necessary to compute

The curve of power output versus load torque for this example motor is shown in Figure 9. It must be noted that the above analysis is valid for the assumption that motor current produced fields do not have a measurable effect on the magnitude and phase of the flux generated by the rotating permanent magnets and also that a constant average flux exists in the air-gap between rotor and stator.

APPENDIX B

CSMP Listing

The system described by the schematic diagram in Figure 4 is programmed in the CSMP language as shown below. The computer used was an IBM 370 located in the W. R. Church Computer Center at the Naval Postgraduate School. Following the program listing is a User's Guide for the recommended procedure in setting the constants and parameters for validation with measured motor performance. Also included are typical output waveforms for a step input of supply voltage.

FILE: BMTBA CSMP A1

```
//JRBTR001 JOB (C169,C323),'MACMILLA-12',CLASS=G,MSGLEVEL=(1,1)
//*MAIN ORG=NPGVM1.0165P,LINES=999
//*FORMAT PR,DDNAME=,DEST=LOCAL
//*FORMAT PR,DDNAME=SYSVECTR,DEST=LOCAL
//CSMPSTEP  EXEC CSMPVDV,PCPDIRS=MYDIRS
//X.SYSIN DD *

* PATCHES FROM 10C INSTALLED
* VERSION ELEVEN -- SIXTH REVISION INCORPORATING THESVS UTIL.
* THIS VERSION INCORPORATES REVERSING COMMUTATION AT REVTIM.
* CURRENTS ARE NOT SUPERPOSED. FLUX * CURRENT IS COMPUTED FOR EACH PHASE
* AND THE RESULTING TORQUES ARE SUMMED.
* THE PURPOSE OF VERSION FIVE IS TO TREAT THE FLUX AS VARYING
* ACCORDING TO THE SUM OF A FUNDAMENTAL SINUSOID
* AND ITS FIFTH HARMONIC AS EXPLAINED IN CHAPTER FIVE.(THOMAS)
* THE TOTAL FLUX IS APPROXIMATED AS THE ALGEBRAIC SUM OF THE FLUX
* DEVELOPED IN TWO WINDINGS AT A TIME TO CALCULATE THE TORQUE
* COEFFICIENT AND BACK EMF COEFFICIENT.
* THIS MODEL SIMULATES MAGNETIC FLUX AS A SINUSOID AND A FIFTH
* HARMONIC AND SIMULATES DIODE COMMUTATION AS WELL AS THE SWITCHING
* LOGIC AND TRANSISTOR DYNAMICS OF A BRUSHLESS DC MOTOR POWER
* CONDITIONER.  THE WINDINGS ARE NOT TREATED INDEPENDENTLY
* AND THEIR TRANSIENT ELECTRICAL INTERRELATION IS SIMULATED,
* THE CONTRIBUTIONS TO DEVELOPED TORQUE ARE
* TREATED AS SUPERPOSABLE.
*
* THE PROGRAM HAS BEEN MODIFIED TO INCLUDE POWER SUPPLY RESISTANCE,RS.
* WITH THE ADDITION OF RS, THE TRIGGERING VOLTAGE FOR THE TRANSISTOR
* PROTECTING DIODES HAS BEEN CHANGED TO INSURE PROPER OPERATION.
*
*
*
INITIAL
*
CONSTANT KTM = 15.86, EX = 0.01465, BL = 0.00, JL = 0.0, N = 1.0, ...
 JM = 0.001, KBM = 0.1120, PI = 3.14159265, KK3 = 3.590,KADJ =.63, ...
 THADV=  0.0, RS= 8.33, ICIMC = 0.01
*
PARAMETER LA = .0008, RA = 0.6850, TLI= 0.0
PARAMETER VSAT = .4, RSAT= .05, RCUT = 1.0E+4
PARAMETER TTIME = 1.0E-6, REVTIM = 0.10
PARAMETER VD1D=0.,VD2D=0.,VD3D=0.,VD4D=0.,VD5D=0.,VD6D=0.
PARAMATER VSGREF = 30.0, KINT = 10000.0, KRAMP = 18250.0
*
*
* KTM -- MFG SUPPLIED MOTOR TORQUE CONSTANT (OZ-IN/AMP)
* KT -- PHASE TORQUE CONSTANT (OZ-IN/AMP)
* KBM -- MFG SUPPLIED MOTOR BACK EMF CONSTANT (VOLT/RAD/SEC)
* KB -- PHASE BACK EMF CONSTANT (VOLT/RAD/S)
* KADJ -- ADJUSTMENT FACTOR FOR MFG SUPPLIED MOTOR CONSTANTS
* RA -- PHASE RESISTANCE OF THE MOTOR (OHM)
* LA -- PHASE INDUCTANCE OF THE MOTOR (HENRIES)
* BM -- VISCOUS FRICTION COEFFICIENT OF THE MOTOR (OZ-IN/RAD/S)
* BL -- VISCOUS FRICTION COEFFICIENT OF THE LOAD (OZ-IN/RAD/S)
* BLP -- VISCOUS FRICTION COEFFICIENT OF LOAD THRU REDUCTION GEARS
* B -- TOTAL VISCOUS FRICTION OF THE MOTOR SYSTEM (SEE BELOW,NO-SORT)
* JM -- INERTIA OF THE MOTOR (OZ-IN/S-S)
* JL -- INERTIA OF THE LOAD   "   "   "
* JLP -- INERTIA OF THE LOAD THRU REDUCTION GEARS
* J -- TOTAL INERTIA OF THE MOTOR SYSTEM (SEE BELOW, NO-SORT SECTION)
* A2 = J/B  --  THE MECHANICAL TIME CONSTANT OF THE MOTOR (SEC)
* ABTAU = LA/(RA+REQAB) -- THE ELECTRICAL TIME CONSTANT OF THE MOTOR
*          AND DRIVE TRANSISTORS FOR CURRENT PATH A-B
* BCTAU = LA/(RA+REQBC) -- THE ELECTRICAL TIME CONSTANT OF THE MOTOR
*          AND DRIVE TRANSISTORS FOR CURRENT PATH B-C
* CATAU = LA/(RA+REQCA) -- THE ELECTRICAL TIME CONSTANT OF THE MOTOR
*          AND DRIVE TRANSISTORS FOR CURRENT PATH C-A
* VIF =  1/2 SUPPLY VOLTAGE, VIN, MEASURED FROM + TO MID POSITION,N
* VIB =  1/2 SUPPLY VOLTAGE, VIN, MEASURED FROM - TO MID POSITION,N
* RQ#  -- EQUIVALENT CIRCUIT RESISTANCE OF Q(#)
* Q#EXP = EXPONENTIAL MODEL FOR TRANSISTION BETWEEN SATURATION AND CUTOFF
```

```
* RSAT = EQUIVALENT CIRCUIT RESISTANCE OF TRANSISTOR SATURATION
* RCUT = EQUIVALENT CIRCUIT RESISTANCE OF TRANSISTOR CUTOFF
* TTIME -- SWITCHING TIME OF TRANSISTOR
* THRST --THIS IS THDEG WHICH IS SET TO ZERO AT START, RESET TO ZERO
*         AT 360 DEG AND CAN ALSO BE USED AS SIMULATION SIDE ANGLE.
* THADV -- THETA ADVANCE FOR COMMUTATION (CCW IS POSITIVE)
* THCON -- COMMUTATION CONTROL ANGLE=THRST+THADV IN DEGREES
* RS --- INTERNAL RESISTANCE OF THE SUPPLY VOLTAGE

NOSORT
   KT=KTM*KADJ
   KB=KBM*KADJ
   BLP = BL/(N**2)
   JLP = JL/(N**2)
   J = JM + JLP
   B = BM + BLP
   A1 = LA / RA
   A2 = J / B
   A3 = LA/(RA +RSAT)
   RS1=RS/2.0
   RS2=RS/2.0
   VINIC = 15.0/KINT

METHOD STIFF
DYNAMIC
   VIF= VINHAF
   VIB =-VINHAF
   VIN = VIF - VIB
*  VSGDEL = (VSGREF - VSG)/2.0
*  VSGERR = DEADSP( -0.5, +0.5, VSGDEL)
*  VININT = INTGRL(VINIC, VSGERR)
*  VINHFG = KINT * VININT
   VINHAF = VINHF1 - VINHF2
   VRAMP1 = RAMP(0.0)
   VRAMP2 = RAMP(0.001)
   VINHF1 = KRAMP*VRAMP1
   VINHF2 = KRAMP*VRAMP2
*
* INTRODUCE FINITE TRANSITION TIME FOR TRANSISTOR SWITCH
* BY INCORPORATING EXPONENTIAL RISE AND DECAY INTO SW1--SW6
* Q#EXP PROVIDES A REALISTIC EXPONENTIAL TRANSITION BETWEEN CUTOFF
* AND SATURATION WHICH INCLUDES SATURATION DELAY WHEN PUT THROUGH
* THE LIMITER

   Q1EXP = REALPL(.75, TTIME, 0.75-SW1)
   Q2EXP = REALPL(0.75, TTIME, 0.75-SW2)
   Q3EXP = REALPL(0.75, TTIME, 0.75-SW3)
   Q4EXP = REALPL(0.75, TTIME, 0.75-SW4)
   Q5EXP = REALPL(0.75, TTIME, 0.75-SW5)
   Q6EXP = REALPL(0.75, TTIME, 0.75-SW6)
RELERR Q1EXP=0.1, Q2EXP=0.1, Q3EXP=0.1, Q4EXP=0.1, Q5EXP=0.1, Q6EXP=0.1
ABSERR Q1EXP=0.1, Q2EXP=0.1, Q3EXP=0.1, Q4EXP=0.1, Q5EXP=0.1, Q6EXP=0.1
   RQ1 = LIMIT(RSAT, RCUT, 2.*RCUT*Q1EXP)
   RQ2 = LIMIT(RSAT, RCUT, 2.*RCUT*Q2EXP)
   RQ3 = LIMIT(RSAT, RCUT, 2.*RCUT*Q3EXP)
   RQ4 = LIMIT(RSAT, RCUT, 2.*RCUT*Q4EXP)
   RQ5 = LIMIT(RSAT, RCUT, 2.*RCUT*Q5EXP)
   RQ6 = LIMIT(RSAT, RCUT, 2.*RCUT*Q6EXP)

* LINEAR DIODE MODEL
* DIODE TURN-ON VOLTAGES
   VD1D = 6000.0 - VAIND + VCIND
   VD6D = 6000.0 + VCIND - VBIND
   VD3D = 6000.0 - VBIND + VAIND
   VD2D = 6000.0 + VAIND - VCIND
   VD5D = 6000.0 - VCIND + VBIND
   VD4D = 6000.0 + VBIND - VAIND
   RD1 = FCNSW(VD1D, RSAT, RCUT, RCUT)
   RD2 = FCNSW(VD2D, RSAT, RCUT, RCUT)
   RD3 = FCNSW(VD3D, RSAT, RCUT, RCUT)
   RD4 = FCNSW(VD4D, RSAT, RCUT, RCUT)
   RD5 = FCNSW(VD5D, RSAT, RCUT, RCUT)
```

```
      RD6 = FCNSW(VCCD, RSAT, RCUT, RCUT)
*
* THE THEVENIN EQUIVALENT CIRCUIT METHOD IS USED WITH THE SUPPLY
* VOLTAGE MID-POINT,N, AS REFERENCE AND THE LOOP METHOD OF ANALYSIS
* APPLIED TO COMPUTE THE PHASE CURRENTS.
*
* THEVENIN EQUIVALENT VOLTAGES
      VANTH = VN1*REQAS2/(REQAS1+REQAS2) + VN2*REQAS1/(REQAS1+REQAS2)
      VBNTH = VN1*REQBS2/(REQBS1+REQBS2) + VN2*REQBS1/(REQBS1+REQBS2)
      VCNTH = VN1*REQCS2/(REQCS1+REQCS2) + VN2*REQCS1/(REQCS1+REQCS2)
*
* TRANSISTOR/DIODE EQUIVALENT RESISTANCE
      REQA1 = RQ1 * RD1/(RQ1+RD1)
      REQA2 = RQ2 * RD2/(RQ2+RD2)
      REQB1 = RQ3 * RD3/(RQ3+RD3)
      REQB2 = RQ4 * RD4/(RQ4+RD4)
      REQC1 = RQ5 * RD5/(RQ5+RD5)
      REQC2 = RQ6 * RD6/(RQ6+RD6)
*
* COMPUTATION OF THEVENIN EQUIVALENT RESISTANCE
*
      REQAS1 = REQA1 + RS1
      REQAS2 = REQA2 + RS2
      REQBS1 = REQB1 + RS1
      REQBS2 = REQB2 + RS2
      REQCS1 = REQC1 + RS1
      REQCS2 = REQC2 + RS2
* THEVENIN EQUIVALENT RESISTANCE
      REQA = REQAS1 * REQAS2/(REQAS1+REQAS2)
      REQB = REQBS1 * REQBS2/(REQBS1+REQBS2)
      REQC = REQCS1 * REQCS2/(REQCS1+REQCS2)
*
* TOTAL LOOP RESISTANCE
      REQAB = 2.*RA + REQA + REQB
      REQBC = 2.*RA + REQB + REQC
      REQCA = 2.*RA + REQC + REQA
*
* LOOP CURRENT- MAXIMUM VALUE
      IAB = (VANTH - VBNTH)/REQAB
      IABA = +(VIN + VEMFB - VEMFA)/(RS + 2.*RA + REQB2 + REQA1)
      IBC = (VBNTH - VCNTH)/REQBC
      IBCA = -(VIN + VEMFB - VEMFC)/(RS + 2.*RA + REQC1 + REQB2)
      ICA = (VCNTH - VANTH)/REQCA
      ICAA = -(VIN + VEMFC - VEMFA)/(RS + 2.*RA + REQA1 + REQC2)
*
* TIME CONSTANTS
      ABTAU = 2.* LA/REQAB
      BCTAU = 2.* LA/REQBC
      CATAU = 2.* LA/REQCA
*
* LOOP CURRENTS
      IMAB = REALPL(0.0,ABTAU,IAB)
      IMBC = REALPL(0.0,BCTAU,IBC)
      IMCA = REALPL(0.0,CATAU,ICA)
* NET LEG (PHASE) CURRENTS
      IMA = IMAB - IMCA
      IMB = IMBC - IMAB
      IMC = IMCA - IMBC
      IMCD = DERIV(0.0,IMC)
      IMCDR = TCIMC*IMCD
      IMCAC = REALPL(0.0,TCIMC,IMCDR)
      IMF = REALPL(0.0,0.005,IM)
      VSGF = REALPL(0.0,0.005,VSG)
*
* INDUCTOR INDUCED VOLTAGES
      DIADT = DERIV(0.0, IMA)
      DIBDT = DERIV(0.0, IMB)
      DICDT = DERIV(0.0, IMC)
      VAIND=LA*DIADT
      VBIND=LA*DIBDT
      VCIND=LA*DICDT
* PHASE CUR'S LA, VOLTAGE
```

```
      VAOLV=IMA*(RA)
      VBOLV=IMB*(RA)
      VCOLV=IMC*(RA)
*     PHASE VOLTAGE
      VAO = IMA*(RA)+LA*DIADT+VEMFA
      VBO = IMB*(RA)+LA*DIBDT+VEMFB
      VCO = IMC*(RA)+LA*DICDT+VEMFC
*
*     COMPUTATION OF POWER SUPPLY TERMINAL VOLTAGES (GND REF)
*     WHERE VIN IS SUPPLY VOLTAGE AND IM IS SUPPLY CURRENT
      VSG = VIN - IM*RS
      VAG = VSG * REQA2/(REQA1 + REQA2)
      VBG = VSG * REQB2/(REQB1 + REQB2)
      VCG = VSG * REQC2/(REQC1 + REQC2)
      VAC = VAG - VCG
*     VOLTAGES ACROSS TRANSISTORS AND DIODES
      VQD1 = VSG - VAG
      VQD2 = VAG
      VQD3 = VSG - VBG
      VQD4 = VBG
      VQD5 = VSG - VCG
      VQD6 = VCG
*
      PVAG = LIMIT (-60., 60., VAG)
      PVBG = LIMIT (-60., 60., VBG)
      PVCG = LIMIT (-60., 60., VCG)
      PVAC = PVAG-PVCG
      PVBA = PVBG-PVAG
      PVCB = PVCG-PVBG
*
      IQ1 = FCNSW(SW1, .003, .003, IMA)
      IQ2 = FCNSW(SW2, .003, .003, IMA)
      IQ3 = FCNSW(SW3, .003, .003, IMB)
      IQ4 = FCNSW(SW4, .003, .003, IMB)
      IQ5 = FCNSW(SW5, .003, .003, IMC)
      IQ6 = FCNSW(SW6, .003, .003, IMC)
      PQ1 = VDQ1 * IQ1
      PQ2 = VDQ2 * IQ2
      PQ3 = VDQ3 * IQ3
      PQ4 = VDQ4 * IQ4
      PQ5 = VDQ5 * IQ5
      PQ6 = VDQ6 * IQ6
      PQTOT = PQ1 + PQ2 + PQ3 + PQ4 + PQ5 + PQ6
*
*     THE PHASE ANGLES LOOK CONFUSED BUT THE PHASE RELATIONSHIP IS RIGHT
      BEMFA =(3.*SIN(2.*THETA+(11*PI/6))+.59*SIN(10.*THETA+(1*PI/6)))
      BEMFB =(3.*SIN(2.*THETA+(7*PI/6))+.59*SIN(10.*THETA+(5*PI/6)))
      BEMFC =(3.*SIN(2.*THETA+(3*PI/6))+.59*SIN(10.*THETA+(5*PI/6)))
*     NORMALIZE LEG EMF
      VEMFA = BEMFA * KB/KK3 * WM
      VEMFB = BEMFB * KB/KK3 * WM
      VEMFC = BEMFC * KB/KK3 * WM
      VEMFAC = VEMFA-VEMFC
      VEMFBA = VEMFB-VEMFA
      VEMFCB = VEMFC-VEMFB
*
*     TORQUE TO MAKE MOTOR TURN
      TA = IMA * KT * BEMFA/KK3
      TB = IMB * KT * BEMFB/KK3
      TC = IMC * KT * BEMFC/KK3
      TM = TA + TB + TC
      TMM = KT * IM
      TBM = BM * WM
      VKBWM = KB*WM
*     TORQUE INTEGRAL VALUE
      TMINT=INTGRL(0.0,TM)
*
      TL = TLL*STEP(1.0E-3)
*
      TN2 = TN1 * (1.0/B)
      WM = REALPL(0.0,A2,TN2)
      WMINT = INTGRL(0.0,WM)
```

```
* WM=320.4425
  WMRPM = WM * (30./PI)
  WMRPMF = WMRPM/N
  THETA = INTGRL(0.0,WM)
  THDEG = THETA * (180.0/PI)
*
* COMMUTATION ADVANCE HERE
  THCON = THRST+THADV
*
  PWRMI = WM * TM * .0070625
  PWRM = EM * .0070675 * WM**2
  PWR = EL * .0070675 * WM**2
  IL = VIN/(2*ROUT)
*
* THIS PROCEDURE PROVIDES A SIMPLE MECHANISM FOR REVERSING THE MOTOR'S
* DIRECTION WHILE KEEPING THE LOAD AS AN OPPOSING TORQUE.

PROCEDURE TN1=FWDBWD(WM,TM,TL)
  IF(WM.LT.0.0) GO TO 1
    TN1 = TM - TL
    GO TO 5
 1  TN1 = TM + TL
 5  CONTINUE
ENDPROCEDURE

* THIS PROCEDURE RESETS THE VARIABLE THRST TO 0 AFTER EVERY 360 DEGREES
* OF MECHANICAL ROTATION.  THIS IS FUNDAMENTAL TO THE SIMULATION OF ALL
* SWITCHING AND POSITION SENSING ACTION.

PROCEDURE THRST=RESET(THDEG)
    THRST = AMOD(THDEG, 360.)
    IF(THRST .LT. 0.0) THRST = THRST + 360.
ENDPROCEDURE

* THIS PROCEDURE WAS TAKEN FROM THE NEXT PROCEDURE BECAUSE THE HALL
* SENSORS SHOULD GENERATE A SINGLE VALUED FUNCTION OF POSITION
* REGARDLESS OF DIRECTION OF ROTATION
PROCEDURE SE1,SE2,SE3=HALL(THCON)
  IF(THCON .GE.180.) GO TO 45
  GO TO 46
45  THCON = THCON - 180.
46 CONTINUE
  IF(THCON .GE.  0..AND. THCON .LT. 30.) GO TO 10
  IF(THCON .GE. 30..AND. THCON .LT. 60.) GO TO 11
  IF(THCON .GE. 60..AND. THCON .LT. 90.) GO TO 12
  IF(THCON .GE. 90..AND. THCON .LT.120.) GO TO 13
  IF(THCON .GE.120..AND. THCON .LT.150.) GO TO 14
  IF(THCON .GE.150..AND. THCON .LT.180.) GO TO 15
 10 SE1 = 1.
    SE2 = 0.
    SE3 = 1.
    GOTO 20
 11 SE1 = 1.
    SE2 = 0.
    SE3 = 0.
    GOTO 20
 12 SE1 = 1.
    SE2 = 1.
    SE3 = 0.
    GOTO 20
 13 SE1 = 0.
    SE2 = 1.
    SE3 = 0.
    GOTO 20
 14 SE1 = 0.
    SE2 = 1.
    SE3 = 1.
    GOTO 20
 15 SE1 = 0.
    SE2 = 0.
    SE3 = 1.
 20 CONTINUE
```

```
ENDPROCEDURE

* THIS PROCEDURE SIMULATES GENERAL COMMUTATION,
* DETERMINES THE ALGEBRAIC SUM OF
* THE VARIABLE FLUX COMPONENTS FOR USE IN COMPUTING THE MOTOR'S
* APPROXIMATE BACK EMF (BEMFI). IT ALSO SUBTRACTS THE GENERATED
* VOLTAGE FROM THE PROPER SUPPLY VOLTAGE.
* SW1 THRU SW6
* SIMULATE POWER TRANSISTOR TRIGGERS BEING ENERGIZED OR SWITCHED OFF
* THCON IS THE VARIABLE THROUGH WHICH THE SWITCHING LOGIC
* IS IMPLEMENTED. REVTIM IS THE TIME AT WHICH CLOCKWISE COMMUTATION
* BEGINS.

PROCEDURE SW1,SW2,SW3,SW4,SW5,SW6,BEMFI,VN1,VN2 =COMM(TIME,...
REVTIM,THCON,BEMFA,BEMFB,BEMFC,VEMFA,VEMFB,VEMFC)
   IF(TIME .GT.REVTIM ) GO TO 100
      THCON1 = AMOD(THCON, 180.)
      IF(THCON1 .LT. 0.0) THCON1 = THCON1 + 180.
   IF(THCON1 .GE.  0..AND. THCON1 .LT. 30.) GO TO 50
   IF(THCON1 .GE. 30..AND. THCON1 .LT. 60.) GO TO 51
   IF(THCON1 .GE. 60..AND. THCON1 .LT. 90.) GO TO 52
   IF(THCON1 .GE. 90..AND. THCON1 .LT.120.) GO TO 53
   IF(THCON1 .GE.120..AND. THCON1 .LT.150.) GO TO 54
   IF(THCON1 .GE.150..AND. THCON1 .LT.180.) GO TO 55
* CLOCKWISE COMMUTATION
100 CONTINUE
   IF(THCON1 .GE.  0..AND. THCON1 .LT. 30.) GO TO 53
   IF(THCON1 .GE. 30..AND. THCON1 .LT. 60.) GO TO 54
   IF(THCON1 .GE. 60..AND. THCON1 .LT. 90.) GO TO 55
   IF(THCON1 .GE. 90..AND. THCON1 .LT.120.) GO TO 50
   IF(THCON1 .GE.120..AND. THCON1 .LT.150.) GO TO 51
   IF(THCON1 .GE.150..AND. THCON1 .LT.180.) GO TO 52
 50 SW1 = 0.
    SW2 = 0.
    SW3 = 0.
    SW4 = 1.
    SW5 = 1.
    SW6 = 0.
    BEMFI = BEMFC - BEMFB
    VN1 = VIF - VEMFC
    VN2 = VIB - VEMFB
    IM=IMC
    GO TO 60
 51 SW1 = 1.
    SW2 = 0.
    SW3 = 0.
    SW4 = 1.
    SW5 = 0.
    SW6 = 0.
    BEMFI = BEMFA - BEMFB
    VN1 = VIF - VEMFA
    VN2 = VIB - VEMFB
    IM=IMA
    GO TO 60
 52 SW1 = 1.
    SW2 = 0.
    SW3 = 0.
    SW4 = 0.
    SW5 = 0.
    SW6 = 1.
    BEMFI = BEMFA - BEMFC
    VN1 = VIF - VEMFA
    VN2 = VIB - VEMFC
    IM=IMA
    GO TO 60
 53 SW1 = 0.
    SW2 = 0.
    SW3 = 1.
    SW4 = 0.
    SW5 = 0.
    SW6 = 1.
    BEMFI = BEMFB - BEMFC
```

```
      VN1 = VIF - VEMFB
      VN2 = VIB - VEMFC
      IM=IMB
      GO TO 60
 54   SW1 = 0.
      SW2 = 1.
      SW3 = 1.
      SW4 = 0.
      SW5 = 0.
      SW6 = 0.
      BEMFT = BEMFB - BEMFA
      VN1 = VIF - VEMFB
      VN2 = VIB - VEMFA
      IM=IMB
      GO TO 60
 55   SW1 = 0.
      SW2 = 1.
      SW3 = 0.
      SW4 = 0.
      SW5 = 1.
      SW6 = 0.
      BEMFT = BEMFC - BEMFA
      VN1 = VIF - VEMFC
      VN2 = VIB - VEMFA
      IM=IMC
 60   CONTINUE
ENDPROCEDURE

TERMINAL
   TITLE BASIC DC MOTOR SYSTEM
   TIMER FINTIM = .050, OUTDEL = .0000275, PRDEL = .000275,...
           DELMIN=1.0E-10
   FINISH THRST = 400.0
   PRINT WM, WMREM, THRST,IM,IMINI,IMIN1,WMINI,IAV,TAV,WMAV, ...
    VAIND, VBIND, VCIND,VN1,VN2, VAC,VBC,VCC,D3,VCD4,VCD5,VCD6, ...
    VSG,VAG,VBG,VCG,VD1D,VD2D,VD3D,VD4D,VD5D,VD6D, ...
    IAB,IABA,IBC,IBCA,ICA,ICAA,IM,TRDEG, THCON,THCON1, ...
    IMA, IMB, IMC, EMF,VIN,VINHAF,IMCAC,VSGF,IMM,TEM,VKEWM
   LABEL  PHASE C CURRENT - AMPS
   OUTPUT TIME, IMC,SW2
   PAGE XYPLOT
         END
   RESET PRINT
   LABEL  POWER SUPPLY CURRENT TO MOTOR - AMPS
   OUTPUT TIME, IM,SW4
   PAGE XYPLOT
         END
   LABEL MOTOR SPEED - RPM
   OUTPUT TIME, WMREM,SW5
   PAGE XYPLOT
         END
   LABEL  POWER SUPPLY TERMINAL VOLTAGE - VOLTS
   OUTPUT TIME, VSG,SW6
   PAGE XYPLOT
         END
   LABEL TOTAL DEVELOPED TORQUE - OZ-IN
   OUTPUT TIME, TM,SW1
   PAGE XYPLOT
         END
   LABEL HP-FILTERED PHASE C CURRENT - AMPS
   OUTPUT TIME, IMCAC,SW3
   PAGE XYPLOT
         END
   LABEL VOLTAGE ACROSS A-C TERMINALS - VOLTS
   OUTPUT TIME, VAC,SW3
   PAGE XYPLOT
         END
   LABEL  LP-FILTERED POWER SUPPLY CURRENT -AMPS
   OUTPUT TIME, IMF,SW5
   PAGE XYPLOT
         END
   LABEL BACK EMF PHASE C - VOLTS
```

```
  OUTPUT TIME, VEMFC,SW1
  PAGE XYPLOT
       END
  LABEL IM DEVELOPED TORQUE - OZ-IN
  OUTPUT TIME, TMM,SW3
  PAGE XYPLOT
       END
  LABEL   POWER OUTPUT - WATTS
  OUTPUT TIME, PWR,SW5
  PAGE XYPLOT
       END
  LABEL LP-FILTERED SUPPLY TERMINAL VOLTAGE - VOLTS
  OUTPUT TIME, VSGF,SW1
  PAGE XYPLOT
       END
       STOP
ENDJOB
/*
//DISSPOP.MYDIRS DD *
   DRAW=1-END,
   MODIFY=1-END(3)  (SIZE=8.,3.),
   MODIFY=2-END(3)  (OVERPLOT,CORNER=0.,3.,SIZE=8.,3.),
   MODIFY=3-END(3)  (OVERPLOT,CORNER=0.,3.,SIZE=8.,3.)
//
```

Users Guide

The following procedures are recommended to be used in running the CSMP language program given in Appendix B:

1. Obtain the motor, load and power supply/conditioner data from the manufacturer and enter the values in INITIAL section at the beginning of the program.
2. Set parameter KRAMP to the desired input voltage V as follows: example V = 30 volts, KRAMP = $\frac{V}{2} \times 10^3$ = 15000. Under these conditions, a fast terminated-ramp input results. This is equivalent to a step input of V volts.
3. The constant KADJ must be set experimentally to produce the measured motor Back EMF voltage. To do this, remove the asterisk in the statement

   * WM = 320.4475

   where 320.4475 is the magnitude of the driver motor speed in rad/sec. (in this case, speed = 3060 RPM). Run the program with different values of KADJ until the Back EMF across 2 windings agree in magnitude with the measured value obtained from the motor.
4. Set N to the value of the speed reduction from motor shaft to load shaft.
5. Set RS to the value of the power supply interval resistance and LA and RA to the per phase winding values.
6. Set RSAT and VSAT values for the power transistor "ON" values and RCUT to the cut-off resistance value.

7. The value of BM should be calculated from the no-load data as a preliminary value and adjusted experimentally until no-load operation of the model agrees with measured no-load values for the motor. Compute BM as follows:

BM = (KT)(KADJ)(IMNL)/(WMNL)

For example

BM = (15.89)(.63)(0.3)/(320.4)

BM = 0.00937 oz-in/rad per sec.

Notes: 1. The asterisks in column 1 of the program statement makes the statement a comment and disregarded by the CSMP Translator. These statements are the result of program development and are included for future application in the development of the complete actuator model.

2. A set of typical output waveforms are included here to indicate the plot output capabilities of the program which are in the TERMINAL section of the CSMP listing.

3. The load applied to the motor should be adjusted over the range of no-load to near peak load and the performance curves of Figure 12 plotted. The CSMP simulation output can then be checked against these results by entering BL as follows:

BL = TL/WM oz-in/rad per sec

where TL is the load torque (oz-in) WM is the motor speed (rad/sec).

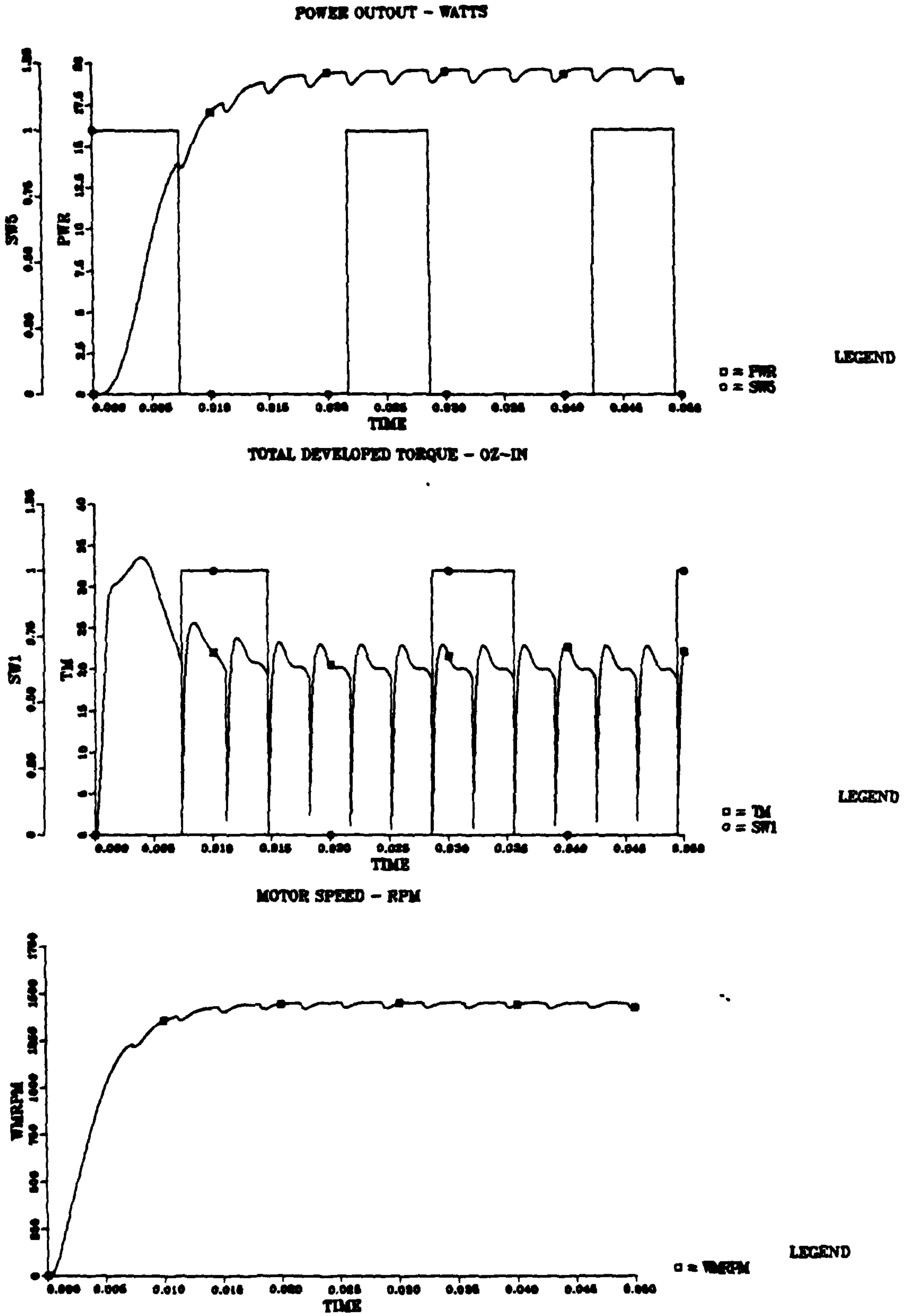

Figure B1 Step Input Response Waveforms

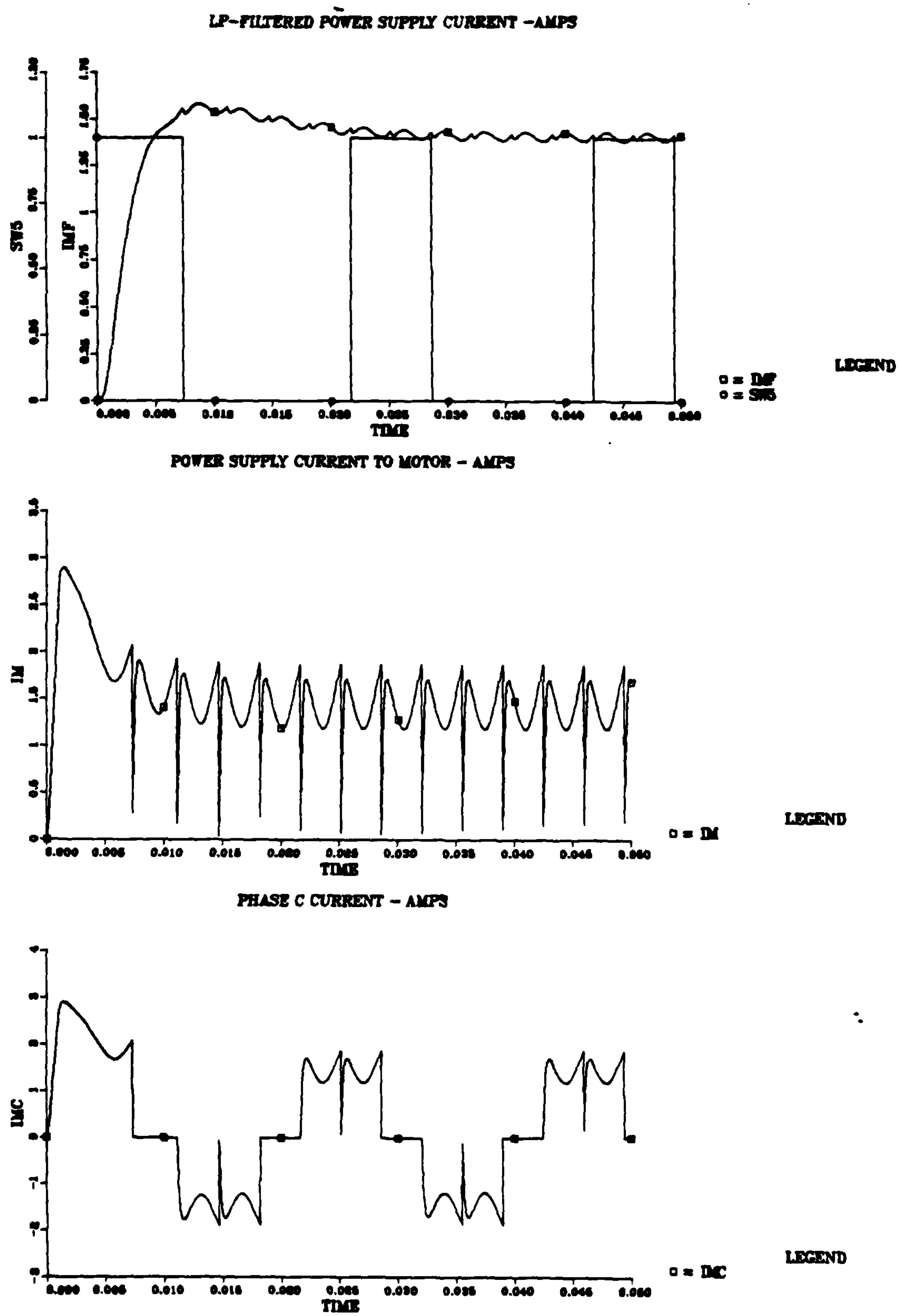

Figure B2 Additional Step Response Waveforms

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